# Analysis of Energy Use in Crisp Frying Processes

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**Abstract**: With increasing energy costs in industrial food frying processes it is essential to identify inefficiencies and minimise them. A way of achieving this is through the application of energy analysis and modelling techniques to characterise the process and investigate the interactions between the various operating and control parameters. The overall objective is to reduce energy consumption without compromising product throughput and quality. This paper provides a review of published work on heat and mass transfer in frying processes. Based on this, a simplified analysis of the key processes has been carried out using an energy balance model. The outputs of this model have been validated using data from an industrial crisp frying facility. The knowledge gained from this validation will be used to better understand and appreciate the energy flows in industrial frying processes and should lead to identification of losses and opportunities for energy recovery.

*Keywords*: Energy use; Frying; Heat and mass transfer; Energy balance model; Energy recovery

## 1. Introduction

Frying is a process of significant importance to the food industry and thus is a field of major interest to engineering and scientific researchers, as well as designers, developers, and manufacturers [1,2]. Frying is considered one of the most complex food-processing operations due to the peculiarities of food as a colloidal-capillary-porous, non-homogeneous and anisotropic material, as well as due to the numerous interactions that take place within the food. Optimum frying processes entail short frying times, high product quality and reasonable costs. In this paper, a general review of published work on heat and mass transfer in frying processes is presented. As a first step, special emphasis is placed on simplified analyses of the key processes using energy balance model.

In the literature numerous research works on deep-fat frying modelling have been carried out [3-8]. Many of these have considered and combined heat and mass transfer principles to describe the temperature and moisture content profiles in a product during the frying processes [9-12]. Some of the early research on mathematical modelling have concentrated on empirical [5,8] and semi-empirical [13] relationships for heat and mass transfer.

Ateba and Mittal [14], considered separate diffusion equations for energy, moisture, and oil phases, without any evaporation term from the product in the energy and moisture transport equation [14]. The analysis included surface evaporation as a boundary condition for the energy equation, and equated the rate of surface evaporation to the rate of diffusive moisture loss at the surface. Diffusion and evaporation of water from the core of the product was not considered even though core temperature exceeded 100 °C. A similar approach was used by Moreira *et.al.* [15] but this time diffusion of energy and moisture were considered.

An unsteady-state heat and mass transfer model in an infinite solid cylinder during oil-frying at 180 °C under the conditions of $0.1<Bi<100$ and $Bi>100$ was proposed by Dincer and Yildiz [16]. A new parameter was defined as a frying coefficient for determination of temperature and moisture distribution. It was concluded that the proposed approach is an effective tool in determining the parameter for cylindrical samples for practical frying applications.

Ikediala *et.al.* [17] carried out modeling of heat transfer in meat patties during single-sided pan-frying using the finite element approach. The evaporation was treated as spatially uniform throughout the material and was included as a sink term in the energy equation.

All the above models have dealt with the frying of a single piece of product and assumed constant physical properties. Although the modelling carried out provided useful insights, the practical importance of this information is rather limited as in industrial scale processing foods are seldom fried as individual products. The models also did not include the oil phase transport.

Farkas *et.al.* [18,19] developed a more detailed model of temperature and moisture transport in deep-fat frying of an infinite potato slab. Separate equations for crust and the core regions, with a moving boundary were considered. They were perhaps the first investigators to consider pressure-driven flow; however they restricted such flow to the crust region and only for the vapour phase. They ignored any diffusion flow in the crust region as well as pressure driven flow of liquid or vapour in the core region. Such non-consideration of fluxes in various regions reduced mathematical complications, but their possible significance was not discussed. Their model did not include the oil phase either.

A one-dimensional transport model that includes oil phase to simulate the effects of different frying conditions on the oil, moisture, and temperature profiles during the frying process of tortilla chips was developed by Chen and Moreira [20]. It was claimed that the model can be used to analyse both a single and a batch of chips. The model, however, did not include the vapour phase separately and therefore the pressure driven mode of transport, which is important and different from diffusion, was not considered.

A multiphase porous media model was developed and applied to microwave heating where significant pressure driven flows can be present [21]. In this model, all transport mechanisms (i.e. molecular diffusion, capillary, and pressure driven flow) and all the phases (i.e. water, vapour, and air) were considered. The model was subsequently used to predict the moisture migration, oil uptake and energy transport in a food material such as a semi-dry potato during deep-fat frying, and were validated with available experimental data [22]. The models did not account for changes in product porosity during frying and their effect on mass transport and energy consumption. Cooling effects during oil absorption were also not considered.

Yamsaengsung and Moreia developed a two-dimensional model based on the approach of [22] to model the frying and cooling processes of tortilla chips. The coupled heat and mass transfer equations were solved using the 2-D finite element method [23,24]. Semi-empirical correlations were developed to take into account the structural changes during frying such as shrinkage and puffing.

More recently, a multiphase porous media model was developed that described heat and mass transfer with strong evaporation inside a potato slab during deep-fat frying [25]. Unlike previous models [22,23], the distributed evaporation (over the food domain) was handled through non-equilibrium formulation, which made the model more effective in describing the physics of the processes. The model which did not consider shrinkage effects was validated against experimental results published in [18].

A complex one-dimensional mathematical model for deep-fat frying in the absence of mechanical deformation was presented by Fasano and Mancini [26]. A four-region process consisting of water saturated region, mixed region, vapour region and crust region with three interfaces were formed and in each region the governing equations were written for temperature and pressure and the corresponding boundary and initial conditions. The model, however, did not consider shrinkage and thus is mainly applicable to the case of thick slabs of food.

Datta [27,28], considered the various methodologies for simultaneous heat and mass transfer modelling in food processes. The fundamental transport modes of molecular diffusion, capillary diffusion and pressure driven Darcy flow were considered. A general multiphase porous media model with distributed evaporation was shown to effectively describe a number of heat and mass transfer processes in foods, particularly processes involving internal evaporation [28].

Achir *et.al.* [29] proposed two inverse models of coupled heat and mass transfer to reconstruct the surface temperature of the product while taking into account possible internal transport of water and the hygroscopic properties of the food matrix during deep-fat frying [29]. It was shown that the combination of front and continuous models is able to describe well the phenomena taking place during frying.

Very recently, a unified approach to food dehydration based on the moving boundary has been presented by Farid and Kizilel [30]. The reported approach was based on previous studies by Farid *et.al.* [31-33]. It is claimed that the method developed can account for moisture diffusion and could be used to predict heat and mass transfer in a wide range of drying and frying processes including deep-fat frying of both thick and thin potato, which usually experience large temperature and moisture changes and distribution.

The majority of the research on frying to date has concentrated mainly on the physical and chemical changes occurring in foods under the influence of high temperature and prolonged heating. Very limited work has been done in extending the research to include energy requirements and energy reduction in industrial frying processes even though this is of significant importance both in terms of Greenhouse Gas (GHG) emissions and economic competitiveness [34,35]. To this end this paper presents a simplified analysis of the key processes using energy balance model based on the first law of thermodynamics. The primary aim is to provide a first approximation of the energy flows and efficiency of the frying process in order to identify and prioritise opportunities for energy conservation measures.

## 2. Materials and methods

In a potato crisp line, shown schematically in Figure 1, the bulk hopper holds the potatoes for the line. A conveyor feeds potatoes from the hopper and the speed is variable to deal with changing feed rates to ensure that the line runs constantly without producing any gaps in the process. From the hopper the potatoes enter the de-stoning and wash unit where they are washed and any stones present are removed by a store removal conveyor. The washed potatoes are then transferred by another conveyor to the peeler. The peeler which is normally a disc with gritted surface peels the potatoes as it rotates. The peelings are washed down with water into a drainage channel below the peeler where they are removed by a drum washer. The potatoes are then inspected and sorted for size before entering the slicer where they are cut into slices of 2-3 mm thickness and 30-40 mm diameter.

The potato slices are then transported to the cold wash rinse unit where they are rinsed with cold water to remove starch solids. The cold water is subsequently destarched and re-used on the process line for potato cleaning. Following cold wash, the potato slices enter the hotwash system to remove sugars and other water soluble solids from the slices.

The washed potato slices then enter a dewatering system where surface water is removed, normally with warm air blown over the potatoes, before the slices enter the fryer. Removal of water from the slices ensures that the frying process is faster and less energy is used to evaporate the water from the potato slice surface.

In the fryer the potato slices are fried in a continuous process in hot oil (170-190 °C), until the moisture content reduces to below 2% by weight. Finally, potato crisps, after travelling along the cooling conveyor belts, are salted, flavoured and vacuum-packed.

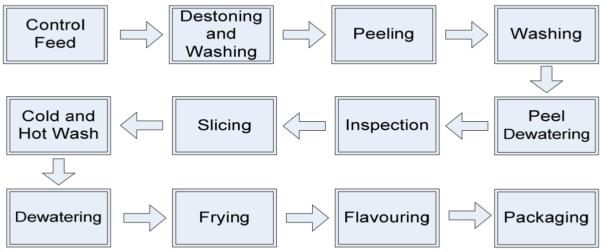


Figure 1. A systemic representation of an industrial frying process.

## 3. Theoretical analysis

In order to determine the primary-energy inputs needed to produce a given amount of product, it is necessary to trace the flow of energy through the relevant industrial crisp manufacturing plant system. Thermodynamic analysis, which is based on the first law of thermodynamics, provides an important technique for the understanding of complex energy systems and thermal process plant, and in particular the optimisation of energy-conversion systems. Figure 2 shows a schematic of the various mass flows in the fryer.

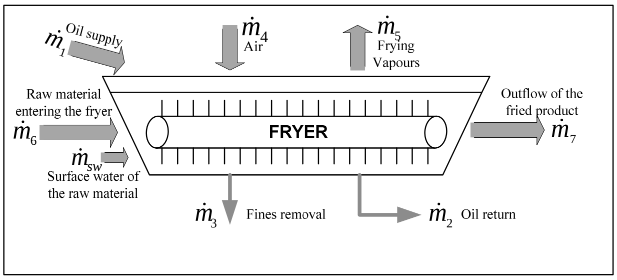


Figure 2. Mass flow balance in the industrial frying process.

The general equation of mass conservation (mass balance) in the process is given by:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad \text{or}$$

$$\dot{m}_1 + \dot{m}_4 + \dot{m}_6 + \dot{m}_{sw} = \dot{m}_2 + \dot{m}_3 + \dot{m}_7 + \dot{m}_5 \qquad (1)$$

where $\dot{m}_{in}$ and $\dot{m}_{out}$ represent the inlet and outlet mass flow rate of the frying system respectively; $\dot{m}_{1,\ldots 7}$ represent various mass flow rates as shown in Figure 2 and $\dot{m}_{sw}$ denotes surface water flow rate associated with the raw product.

In addition, the mass conservation equations of each species can be determined as follows:

Frying oil

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3 + \dot{m}_7 X_{o,7} + \dot{m}_5 X_{o,5} \qquad (2)$$

where $X_{o,7}$ is the ratio of oil to mass flow rate 7, $X_{o,5}$ is the ratio of oil to mass flow rate 5.

Potato solid

$$\dot{m}_6 X_{s,6} = \dot{m}_7 X_{s,7} \qquad (3)$$

where $X_{s,6}$ is the ratio of potato solid to mass flow rate 6 and $X_{s,7}$ is the ratio of potato solid to mass flow rate 7.

Water

$$\dot{m}_6 X_{w,6} + \dot{m}_{sw} = \dot{m}_7 X_{w,7} + \dot{m}_5 X_{v,5} \qquad (4)$$

where $X_{w,6}$ is the ratio of water content to mass flow rate 6, $X_{w,7}$ is the ratio of water content to mass flow rate 7 and $X_{v,5}$ is the ratio of water vapour to mass flow rate 5.

Air

$$\dot{m}_4 = \dot{m}_5 X_{a,5} \quad (5)$$

where $X_{a,5}$ is the ratio of air to mass flow rate 5.

The general form of the energy equation of the system can be expressed in a rate form as

$$\dot{E} = \dot{E}_1 + \dot{E}_2 + \dot{E}_3 + \dot{E}_4 + \dot{E}_5 + \dot{E}_6 \quad (6)$$

where $\dot{E}$ is the total energy, $\dot{E}_1$ is the energy used for raw product heating, $\dot{E}_2$ is the energy needed for water heating and evaporation, $\dot{E}_3$ is the energy needed for oil evaporation, $\dot{E}_4$ is the energy needed for heating air, $\dot{E}_5$ is the energy transmitted through the external surfaces of the fryer to the environment, and $\dot{E}_6$ is the energy lost to the environment through the fryer ventilation.

The individual energy rate constituting the balance by the following equations:

(a) The energy needed for raw potato heating during the whole frying process:

$$\dot{E}_1 = c_{ps} \dot{m}_6 X_{s,6} \left(T_7 - T_6\right) \quad (7)$$

where $c_{ps}$ is the specific heat of the potato solid, $T_7$ is the temperature of the final fried product, $T_6$ is the temperature of the raw material.

(b) The energy needed for heating and evaporating the water contained in the raw material is given below:

$$\dot{E}_2 = \left[c_{pw}\left(T_b - T_6\right) + h_w\right] \cdot \left(\dot{m}_6 X_{w,6} + \dot{m}_{sw} - \dot{m}_7 X_{w,7}\right) \quad (8)$$

where $c_{pw}$ is the specific heat of water, $T_b$ is the temperature of boiling water, $h_w$ is the latent heat of water evaporation.

(c) The energy needed for oil evaporation is given by:

$$\dot{E}_3 = h_o \left(\dot{m}_1 - \dot{m}_2 - \dot{m}_3 - \dot{m}_7 X_{o,7}\right) \quad (9)$$

where $h_o$ is the latent heat of oil.

(d) The energy needed for heating air is given by:

$$\dot{E}_4 = c_{pa} \dot{m}_4 \left(T_5 - T_4\right) \quad (10)$$

where $c_{pa}$ is the specific heat of air, $T_4$ is the temperature of air, $T_5$ is the temperature of frying vapour.

(e) The energy transmitted through the external surfaces of the fryer to the environment can be determined from:

$$\dot{E}_5 = UA\left(T_{fo} - T_{amb}\right) \quad (11)$$

where $U$ is the overall heat transfer coefficient of the casing of the fryer, $A$ is surface area of the casing, subscript $fo$ denotes the frying oil and $amb$ the ambient.

$T_{amb}$ is the average ambient temperature for the location at which the system under consideration operates. In many cases $T_{amb}$ is assumed to be 25 °C.

Using Eqs. (7), (8), (9), (10) and (11), a combined equation for overall energy can be written as:

$$\begin{aligned}\dot{E} = {} & c_{ps} \dot{m}_6 X_{s,6}\left(T_7 - T_6\right) + \\ & [c_{pw}\left(T_b - T_6\right) + h_w] \cdot \left(\dot{m}_6 X_{w,6} + \dot{m}_{sw} - \dot{m}_7 X_{w,7}\right) + \\ & h_o\left(\dot{m}_1 - \dot{m}_2 - \dot{m}_3 - \dot{m}_7 X_{o,7}\right) + c_{pa}\dot{m}_4\left(T_5 - T_4\right) + \\ & UA\left(T_{fo} - T_{amb}\right)\end{aligned} \quad (12)$$

To solve Eq. (12) and determine the energy consumption of frying processes several parameters need to be defined.

For the developed model, which was based on the first law of the thermodynamics, the following main assumptions were made:

(i) the process is a steady flow process;

(ii) heat transfer through the wall of the fryer is very small and can be neglected;

(iii) the heat required for chemical reactions is small compared to the heat required to evaporate the water;

(iv) constant water and air specific heats.

The parameters used in this paper, listed in Table 1, relate to a commercial fryer in service. The operational data relate to the period 1st to 14th December 2009 and the energy consumption determined from the model is validated against energy consumption data from the plant.

| *Symbol* | *Value or expressions* | *Source* |
|---|---|---|
| $A$ | 45 m$^2$ | Measured |
| $c_{pa}$ | 1.006 kJ/kg K | |
| $c_{ps}$ | 1.3 kJ/kg K | Measured |
| $c_{pw}$ | 4.18 kJ/kg K | [28] |
| $h_o$ | 300.0 kJ/kg | Measured |

| | | |
|---|---|---|
| $h_w$ | 2256.7 kJ/kg | |
| $U$ | $1.4\times10^{-3}$ kW/m$^2$ K | [35] |
| $\dot{m}_1$ | 62.84 kg/s | Measured |
| $\dot{m}_2$ | 60.0 kg/s | Assumed |
| $\dot{m}_3$ | 0.2 kg/s | Assumed |
| $\dot{m}_4$ | 2.0 kg/s | Assumed |
| $\dot{m}_5$ | 5.5 kg/s | Assumed |
| $\dot{m}_6$ | 0.99 kg/s | Assumed |
| $\dot{m}_7$ | $m_6\times X_{s,6}\times X_{s,7}$ kg/s | Calculation |
| $\dot{m}_{sw}$ | $10\%\times m_6$ kg/s | Assumed |
| $T_{amb}$ | 298.0 K | Measured |
| $T_{fo}$ | 446.0 K | Measured |
| $T_4$ | $T_4 = T_{amb}$ | |
| $T_5$ | 375.9 K | Measured |
| $T_6$ | 333.0 K | Measured |
| $T_7$ | 423.0 K | Assumed |
| $X_{s,6}$ | 30.0% | Assumed |
| $X_{o,7}$ | 30.3% | Measured |
| $X_{w,7}$ | 1.6% | Measured |

Table 1. Physical properties used in the computation of a batch of potato crisps frying processes.

## 4. Results and discussion

Figure 3 shows a comparison between predicted daily energy consumption from the model and data obtained from the plant over a two week period in December 2009.

The model assumes steady state conditions during the period whereas in the real process there are fluctuations in the throughput and energy consumption which depend on a large number of operational and control factors. Despite this it can be seen that in general there is a good agreement between the predicted and actual energy consumption. The highest discrepancy is for 6 to 10 December where the maximum difference between actual and predicted energy consumption is 16%. This discrepancy can be due to many reasons which the authors are not in a position to quantify and identify at this stage. Most probable reasons are variation of product throughput; in the model a constant sliced potato flow rate of 0.99 kg/s was assumed, and the initial moisture content of the sliced potato which was again assumed constant at 70% (wet basis). The effects of these variables are investigated further in this section.

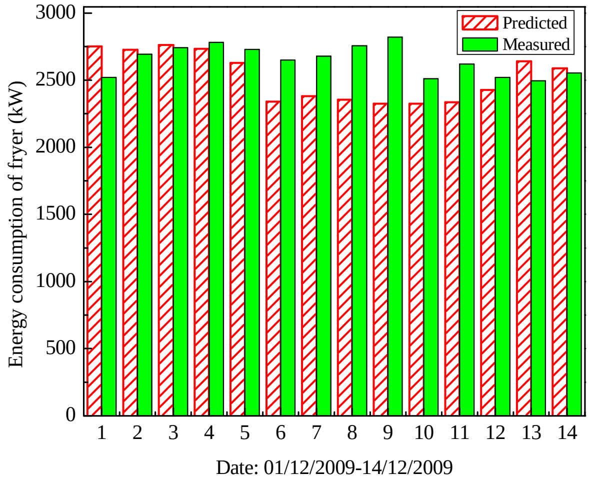


Figure 3. Comparison between data obtained from the plant and calculations from the developed model in this study over the period of December 1st—14th, 2009.

The percentage contribution of the different independent variables on the energy consumption of the fryer predicted by the model using the data in Table 1 is depicted in Figure 4.

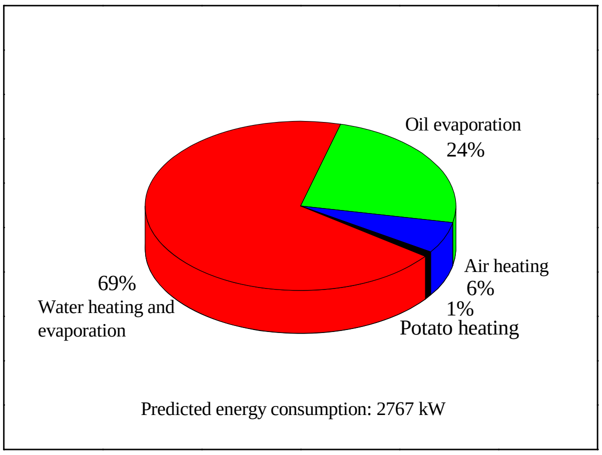


Figure 4. Percentage energy consumption of the fryer.

The total energy consumption of the fryer was found to be 2767 kW. It can be seen from Figure 4 that the energy required for water heating and evaporation is around 70% of the total energy input. Energy input for oil evaporated during the process is approximately 24% of the total whereas energy required to heat the air entrained in the process is 6% and energy for potato slice heating is only around 1%.

The final moisture content of the product is only about 1.5% by weight. The moisture content of potatoes will depend, among others, on their variety and growing conditions. To investigate the effect of moisture content on the energy consumption, 3 different moisture contents (wet basis), 60%, 70% and 80% were considered. Figure 5 shows the variation of the energy consumption of the process as a function of raw material flow rate and moisture content. It can be seen, as expected, that the energy consumption is a linear function of the raw material flow rate. It can also be deduced that the energy consumption is also a linear function of the potato moisture content. At a raw material flow rate of 1.0 kg/s, increasing the moisture content from 70% to 80% increase the energy input to the process from 2790 kW to 3030 kW which is a 9% increase.

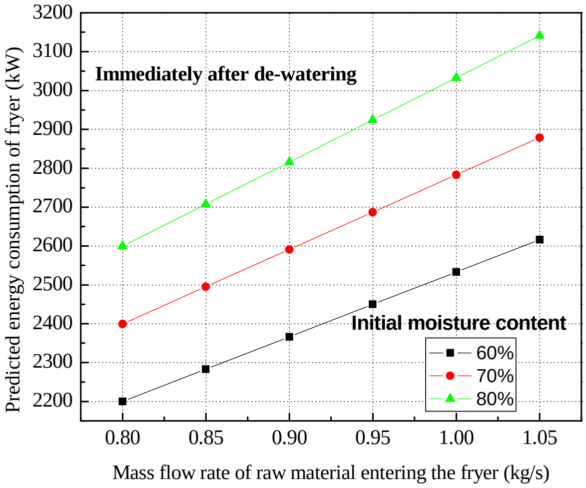


Figure 5. The effect of initial moisture content of raw material on the predicted energy consumption.

Even though before entering the fryer the potato slices are normally dewatered using one of a variety of methods not all the water is removed and this contributes to the energy consumption of the fryer. The impact of surface water on energy consumption is shown in Figure 6 for surface water percentages of between 4% and 10% by weight. It can be deduced that surface water increases the energy input to the process almost linearly. At a raw product mass flow rate of 1.0 kg/s, and surface water of 4% the energy input to the fryer is 2640 kW. Increasing the surface water to 10% increases the energy input to 2785 kW which represents a 5.5% increase. This increase (145 kW) is significant so surface water is an important parameter influencing energy consumption and needs to be considered in frying process optimisation studies.

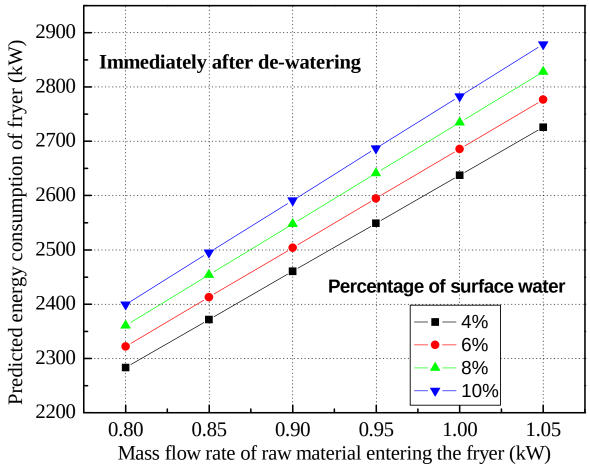


Figure 6. Predicted energy consumption at different percentages of raw materials surface water before entering the fryer.

## 5. Conclusions

In this paper, previous works on heat and mass transfer processes in food frying have been reviewed. The review revealed that the frying models developed so far have been primarily concerned with the frying of individual pieces of food and a number of assumptions to simplify the models. Further work is needed to develop more general and practical frying models to be used in whole process optimisation and control to reduce energy consumption without adversely influencing product quality.

As a first step, a mathematical model based on the first law of thermodynamics to predict the overall energy consumption of potato crisp frying processes has been developed and verified against data from an industrial frying facility. Important parameters that influence the energy consumption are the product throughput and the initial moisture content of the product, which are directly proportional to energy required by the frying process.

Further work will concentrate on refinement of the model and using it to quantify energy flows, losses and energy recovery options.

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**Nomenclature**

| | |
|---|---|
| $A$ | surface area, m$^2$ |
| $Bi$ | Biot number |
| $c_p$ | specific heat, kJ/kg K |
| $\dot{E}$ | energy, kW |
| $h$ | latent heat, kJ/kg |
| $\dot{m}$ | mass flow rate, kg/s |
| $T$ | temperature, K |
| $X$ | composition ratio, % |
| $U$ | overall heat transfer coefficient, kW/m$^2$ K |

*Subscripts*

| | |
|---|---|
| *a* | air |
| *amb* | ambient |
| *b* | boiling water |
| *fo* | frying oil |
| *in* | inlet |
| *o* | oil |
| *out* | outlet |
| *s* | potato solid |
| *sw* | surface water |
| *v* | vapour |
| *w* | water |
| *1* | oil supply |
| *2* | oil return |
| *3* | fines removal |
| *4* | air flow |
| *5* | frying vapour |
| *6* | raw material |
| *7* | fried product |

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